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Palaeoecological data as a tool to predict possible future vegetation changes in the boreal forest zone of European Russia: a case study from the Central Forest Biosphere Reserve

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Abstract. New multi-proxy records (pollen, testate amoebae, and charcoal) were applied to reconstruct the vegetation dynamics in the boreal forest area of the southern part of Valdai Hills (the Central Forest Biosphere Reserve) during the Holocene. The reconstructions of the mean annual temperature and precipitation, the climate moisture index (CMI), peatland surface moisture, and fire activity have shown that climate change has a significant impact on the boreal forests of European Russia. Temperature growth and decreased moistening during the warmest phases of the Holocene Thermal Maximum in 7.0-6.2 ka BP and 6.0-5.5 ka BP and in the relatively warm phase in 3.4-2.5 ka BP led to structural changes in plant communities, specifically an increase in the abundance of broadleaf tree species in forest stands and the suppression of *Picea*. The frequency of forest fires was higher in that period, and it resulted in the replacement of spruce forests by secondary stands with *Betula* and *Pinus*. Despite significant changes in the climatic parameters projected for the 21st century using even the optimistic RCP2.6 scenario, the time lag between climate changes and vegetation responses makes any catastrophic vegetation disturbances (due to natural reasons) in the area in the 21st century unlikely.

1. Introduction

Modern climate changes, which are manifested as an increase in air temperature, changes in precipitation patterns and more prevalent anomalous weather evens such as heat waves and windstorms, have an obviously significant impact on the growth and functioning of boreal forests in Northern Eurasia [1]. To describe future climate variability, it is very important to know how different forest communities will respond to changes in climate conditions in the future [2, 3, 4, 5]. The method of palaeoenvironmental reconstructions is one of the most effective approaches to describe the possible scenarios of the landscape state and vegetation changes in the 21st century [6, 7]. Within the last decades, climate and landscape reconstructions for the Holocene Thermal Maximum (8.0–5.7 ka

BP) and the optimum of the last Interglacial (Eemian, MIS 5e, about 125 ka BP) were applied as palaeo-analogues of the vegetation response considering increases in global temperature of 0.7–1.0°C and 1.7–2.0°C, respectively [7]. Loutre and Berger [8] have suggested that the conditions of the orbital climate forcing during the Holstenian Interglacial (MIS 11, 420–370 ka BP) are the most similar to those of the current interglacial period. Therefore, vegetation dynamics during the Holstenian Interglacial can be used as an analogue to predict the vegetation changes at the end of the 21st century. Multiple Holocene climate reconstruction models for the Eastern and Northern Europe exhibit rapid temperature increases in the Late Glacial and Early Holocene (an analogue of present-day global warming), during the Holocene Thermal Maximum when the mean annual temperatures were 2°C higher than those of the present day [6,9,10,11]. Roughly 5.7–5.5 ka BP, the Holocene Thermal Maximum was followed by gradual climatic cooling that included several warming and cooling phases with temperature fluctuations ranging between 2 and 3°C. The key mechanisms of forest-climate interaction in previous epochs remain unclear, and additional research using aggregated multy-proxy data analysis is necessary.

The present study is focused on reconstructing vegetation dynamics in the southern part of the Valdai Hills at various time intervals during the Holocene. We make use of new multi-proxy palaecological data (pollen, testate amoebae, charcoal, etc.) to interpret past vegetation dynamics. The temporal moistening conditions in the area were derived using the climate moisture index (CMI, [12]). To predict possible regional vegetation changes in the boreal forest zone of central European Russia under climate changes in the 21st century, several scenarios of future vegetation changes are suggested. Available projections of climate change for the 21st century are provided by an ensemble of global climate models such as CMIP5 (IPCC 2013, Coupled Model Intercomparison Project, Phase 5 [1]) for scenarios RCP2.6 and RCP8.5 (Representative Concentration Pathways for possible range of radiative forcing +2.6 W/m^2 and +8.5 W/m^2). These projections show that the mean air temperature for the central part of European Russia may increase at the end of the current century by 2.0–2.5 and 6.0–7.0°C, respectively. This temperature increase will be accompanied by an increase in annual precipitation that may range from 7% (RCP2.6) to 15% (RCP8.5). All of these changes may result in significant alterations in forest cover.

A key region studied in this investigation was the Central Forest State Natural Biosphere Reserve (CFSNBR) situated in the southern part of the Valdai Hills. We opted to focus on the southern boundary of the boreal forest zone. Taking into account the modern trend of increases in global air temperature, forest communities can be very sensitive to environmental changes. A number of very detailed palaeoecological reconstructions of the Holocene climate and vegetation history for the area have been conducted and found to be very useful for this study [6, 13, 14, 15].

For projecting possible vegetation changes in the 21st century, we used the optimistic RCP2.6 climate scenario. The RCP8.5 climatic scenario does not have any analogues in the Holocene, and consequently, it was not used in the present study.

2. Materials and Methods

The CFSNBR is situated roughly 360 km northwest of Moscow (the Tver region, 56º35' N, 32º55' E) in an ecological zone transitioning from taiga to broadleaf forests. The vegetation of the CFSNBR is primary southern taiga forests, and it has been undisturbed by any human activities for at least 86 years. The climate of the study area is temperate and moderately continental with a mean annual temperature is 4.1°C and annual precipitation of roughly 700 mm [4]. The plant cover includes mixed uneven-age spruce (*Picea abies*), birch (*Betula pendula*) and aspen (*Populus tremula*) trees with a small admixture of broadleaf trees (*Tilia cordata, Ulmus laevis, Fraxinus excelsior, Acer platanoides*). Alder (*Alnus glutinosa*) is abundant in the river valleys.

The Holocene vegetation and climate reconstructions are based on palaeoecological data from the large peat bog Staroselsky moch (617 ha), which is located in the southeast part of the CFSNBR. The results of pollen and testate amoebae analysis were published by Novenko et al [14] and Payne et al [15]. The estimation of micro-charcoal concentration in peat core from the small forest peatland (<0.1

ha) located 4 km west of the Staroselsky moch peat bog was used for reconstructing fire frequencies. Available palaeoecological data allowed us to reconstruct environmental changes during the 9000 years, with the exception of the micro-charcoal data, which cover the last 7000 years. The last millennium was excluded from analyses of vegetation-climate interactions due to increasing human impacts and vegetation disturbance.

The mean annual temperature and precipitation during the Holocene (figure 1) were reconstructed with pollen data using the Modern Analogue Technique (MAT). Details of the MAT have been presented in previous publication [13]. Using the MAT, we found a statistically significant analogue in the modern pollen datasets (720 sites in Europe and Siberia) for each fossil pollen assemblage. The climatic characteristics (temperature, precipitation) of the area, where the spectrum analogue was obtained, are accepted as reconstructions of climate and woodland coverage in the past. Climatic information was derived from BRIDGE Earth System Modelling results [16].
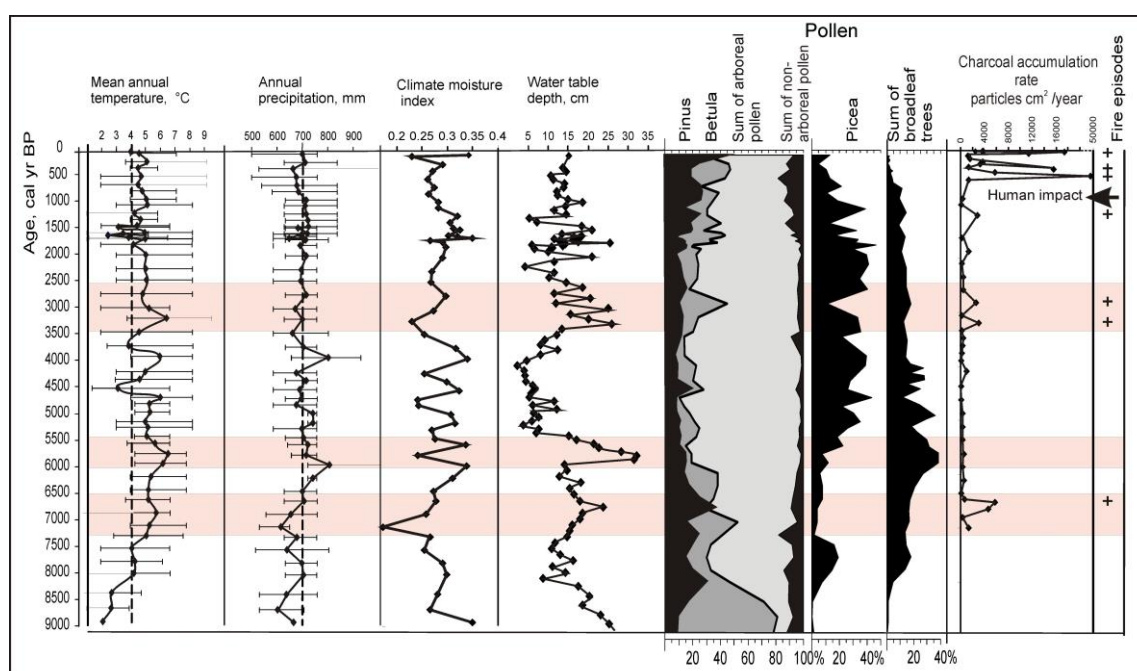
Figure 1. Summary of the results of the multi-proxy palaecological reconstructions for the area of the CFSNBR, including the reconstructions of the mean annual temperature and precipitation (modified after Novenko et al. [14]), climatic moisture index and water table depth inferred by pollen and testate amoebae data from Staroselsky moch peat bog; characteristic of pollen taxa from the pollen records from the Staroselsky moch peat bog; micro-charcoal accumulation rate and fire episodes inferred from charcoal data from the small forest peatland in the area of the CFSNBR. The Sum of broadleaf trees includes pollen of *Quercus, Ulmus, Tilia, Fraxinus, Acer* and *Carpinus*.

Modern analogue calculations were produced using Polygon 2.2.4. A test of the accuracy of the applied method using a database of surface pollen assemblages reveals that the MAT can reproduce the mean annual temperature rather correctly ($R^2=0.81$; RMSEP=1.5°C). The accuracy of reconstruction of annual precipitation is lower ($R^2=0.41$, RMSEP=100 mm), and we can determine changes in humidity only as general trends.

To describe the temporal patterns of moistening conditions within the study area during the Holocene, we computed the CMI [12] using the ratio of annual precipitation to annual potential evapotranspiration. The annual potential evaporation was calculated using the Priestley-Taylor equation [17]. This numerical algorithm uses the reconstructed annual air temperature, the forest cover and pollen proportion of coniferous and deciduous tree species as input parameters.

Peatland surface moisture, a robust proxy for climate humidity, was reconstructed as depth to the water table (WTD, cm) using a testate amoeba-based transfer function (reversed weighted averaging regression model) that was specifically developed for the forest zone of European Russia [18]. The transfer function included 80 samples from 18 peatlands located in the taiga, mixed and broadleaf forests and the forest-steppe zones of European Russia. The leave-one-out cross-validation of models constructed for the training dataset revealed a rather high accuracy of the model (R^2=0.74; RMSEP=5.5 cm). Water-table depths inferred by testate amoeba generally reflected the length and severity of the summer moisture deficit, which in raised bogs is primarily controlled by summer precipitation [19].

Micro-charcoal concentration data were transformed into charcoal accumulation rates (CHAR, particles cm^{-2} yr^{-1}) using CharAnalysis software [20], which separates the long-term trends (i.e., background CHAR) from positive deviations (i.e., charcoal peaks) in the CHAR time series. Charcoal peaks represent fire episodes (i.e., one or more fires that occur during the time span of the peak).

3. Results and discussions

The climate conditions of the study area between 9.0 and 8.0 ka BP were relatively cold (figure 1). The mean annual temperature was 2°C lower then at the present time at the beginning of this period and increased to modern values roughly 8.0 ka BP. The mean annual precipitation increased from 600 to 700 mm and a consistent decrease in peatland surface wetness indicated an increase in climate humidity. The CMI decreased from 0.36 (more humid) to 0.26, which corresponds to less humid, drier conditions. During this period, the study area was occupied mainly by birch forest, which has persisted in the region since the early Holocene [13, 21]. The plant macrofossils revealed from the lower part of the peat core suggested an abundance of *Betula pubescens* [14].

Climate warming after 8.0 ka encouraged the expansion of *Picea*, broadleaf trees (*Quercus, Tilia, Ulmus*) and *Corylus* over the study area. The moistening conditions were characterized by high variability in the CMI between 0.17 (low humidity) and 0.30 (moderate humidity). A high WTD in the peatland inferred from testate amoebae data indicated rather humid conditions during the summer periods between 8.0 and 7.0 ka BP (figure 1).

From 7.0 to 5.5 ka BP, the mean annual temperature was roughly 5–7°C, which exceeds modern-day values by 1–3°C (figure 1). These reconstructions agree well with the climatic conditions determined from pollen data for the Holocene Thermal Maximum in the Baltic region and Fennoscandia [10, 11], where the mean annual temperatures were 2°C higher than those at the present time. Pollen-inferred temperature reconstructions from Estonia have shown that the mean annual temperatures reached 8–9°C, which exceeded modern-day ones by 3.0–3.5°C [22].

The annual precipitation in the CFSNBR was roughly 600 mm during the period 7.0–6.5 ka BP. Between 6.5 and 5.5 ka the annual precipitation approached or exceeded modern-day values. The reconstruction of the peatland surface moisture reflected two distinct phases with drier climate conditions (7.0–6.2 ka BP and 6.0–5.5 ka BP). The CMI in the periods decreased to lowest values 0.24 (for a ratio of annual potential evaporation and precipitation of roughly 0.76), and it was lower as the mean values estimate for entire Holocene for the area (CMI=0.285). The WTD during the second phase in the peat bog was extremely low (32 cm), likely due to the reduced summer precipitation and higher summer temperatures.

The proportion of *Picea* pollen reduced significantly between 7.0 and 5.5 ka BP, and it almost disappeared from assemblages during the second warm phase 7.0–6.2 ka BP. At the same time, *Pinus*, *Betula* and broadleaf tree species increased their abundance. The pollen productivity of wind-pollinated plants, such as *Betula, Alnus* and *Pinus*, is much higher than the pollen productivity of *Acer, Ulmus* and *Tilia*. Therefore, the proportions of broadleaf trees in pollen assemblages are often underestimated [23]. In the period 6.0–5.7 ka BP, the fraction of the sum of broadleaf tree pollen reached 40% of the total pollen sum, indicating a broad expansion of temperate deciduous forests.

The warm and relatively dry climatic conditions of the Holocene Thermal Maximum were unfavorable for *Picea* growth. According to data of modern ecological studies of spruce, *Picea abies*

prefers moist soils with high seasonal water storage [24] and is highly susceptible to drought [25]. The availability of water is therefore an important factor for the growth of this tree species nowadays.

Climate reconstructions of the study area based on the pollen data from Staroselsky moch peatland revealed climate cooling and an increase in humidity after 5.3 ka BP. These reconstructions coincided with a number of palaeoclimatic reconstructions based on various natural archives in Europe that demonstrated gradual climatic cooling since 5.7 ka BP [6,9,10,11,26], possibly caused by a decrease in summer insolation. Roughly 4.5 ka BP, the mean annual temperature in the study area declined to 3°C and the annual precipitation was close to the modern values. At 4.0 ka BP the annual precipitation increased to 800 mm year. The CMI in the period varied significantly and in wetter years reached 0.35. Higher precipitation levels and lower temperatures promote sufficient soil moisture conditions that resulted in an increasing fraction of *Picea* in forest stands in the study area. The share of *Picea* pollen in assemblages from peat core at Staroselsky moch increased to 30–40% (figure 1). Broadleaf trees remained relatively abundant in the plant cover until 4.0 ka BP and then their fraction gradually decreased. The rise of *Picea* pollen values were traced in pollen diagrams from European Russia and Finland [6, 10], which suggested the expansion of boreal coniferous and mixed coniferous-broadleaf forests.

The next warm and drier phase was detected in climate reconstruction by pollen and testate amoebae data from the Staroselsky moch peat bog between 3.4 and 2.5 ka BP. The mean annual temperature exceeded modern-day values by 1–2°C, the WTD in the peatland dropped to 20–25 cm, and the CMI decreased to 0.23. The proportion of *Picea* fell, and the fraction of *Betula* and broadleaf trees increased. One can expect that *Picea* forests were significantly damaged during this phase by fires.

Charcoal data from the area of the CFSNBR have shown that the Holocene fire activity was low until the last millennium. The conditions of the study area— a flat topography with impeded drainage of soils and an abundance of broadleaf tree species—were replaced by *Picea* in a relatively wet climate. This situation obviously led to hampered burning and low fire activity [27]. Only two distinct fire episodes were detected during the warm and dry phase 3.4–2.5 ka BP, and one fire episode occurred roughly 6.6 ka BP, which corresponded to the oldest dry phase of the Holocene Thermal Maximum. Archeological findings and palaeobotanical indicators are inconclusive in terms of human occupation of the study area during these periods. Consequently, one can assume that the cause of the forest fires was likely summer drought.

Climate reconstructions for the study area have demonstrated relatively humid climate conditions after 2.5 ka BP. The CMI in some years reached 0.33. Our data agree well with European palaeoecological records that highlight climate cooling and an increase in humidity roughly 2.5 ka BP [11, 26]. After 2.5 ka BP, spruce forests recovered in the study area. The *Picea* pollen curve formed a conspicuous maximum between 2.5 and 1.6 ka BP (figure 1). The increase in *Picea* pollen values after 2.5 ka BP was also recorded in a number of sites in Finland, European Russia, Belarus and Estonia [10, 21, 22, 28], findings that suggest a regional expansion of spruce forests.

The last 1000 years have been marked by dramatic changes in vegetation. The proportion of spruce and broadleaf trees in the forest stands decreased abruptly, which coincided with the expansion of birch forests. The micro-charcoal concentration increased by an order of magnitude, and the frequency of fire increased. Pollen records from the area of the CFSNBR have revealed a significant reduction in total forest coverage [13], the presence of cultivated cereals, weeds and ruderal plants [14]. These findings apparently indicate human impacts on plant cover.

4. Projection of future vegetation changes and conclusions

Holocene climatic reconstructions have shown a very high sensitivity of vegetation to climate changes. To predict possible forest vegetation changes during the 21st century, the RCP2.6 scenario was used. For vegetation projections, we can use the warm and dry phases observed during the Holocene Thermal Maximum 7.0–6.2 ka BP and 6.0–5.5 ka BP, as well as the climate warming between 3.4 and 2.5 ka BP. The palaeoecological data that we obtained for these periods have shown that the climate

warming and decrease in CMI led to structural changes in plant communities: an increase in the abundance of broadleaf tree species (*Quercus*, *Tilia, Ulmus, Fraxinus, Acer*) in forest stands and the suppression of *Picea* trees. The frequency of forest fires during the aforementioned periods was higher, and it resulted in the replacement of spruce forests by secondary stands containing *Betula* and *Pinus*.

According to our palaeoenvironmental reconstructions, vegetation changes caused by climate warming lasted from 500–1000 years. On the other hand, the observed temperature growth spanned only a few decades. One can expect a lag between climate changes and vegetation response; catastrophic vegetation disturbances are unlikely to occur in the 21st century. Although the palaeoecological data do not fully correspond to the short-term changes expected in the current century, they can be used to assess general trends in vegetation dynamics.

Acknowledgement

References
[1]   IPCC 2013 *IPCC Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the IPCC* (Cambridge: Cambridge University Press) p 1535
[2]   Bonan GB, Pollard D and Thompson SL 1992 *Nature* **359** 716-8
[3]   Brovkin V, Raddatz T, Reick CH, Claussen M and Gayler V 2009 *Geophys. Res. Let.* **36** L07405
[4]   Oltchev A *et al* 2002 *Phys. Chem. Earth* **27**(9-10) 675-90
[5]   Soja AJ *et al* 2007 *Global Planet Change* **56**(3-4) 274-96
[6]   Novenko E, Olchev A, Desherevskaya O and Zuganova I 2009 *Environ Res Let.* **4** 045016
[7]   Velichko AA and Borisova OK 2011 *Dokl. Earth Sci.* **438** 681-5
[8]   Loutre MF and Berger AL 2003 *Global Planet. Change* **36** 209–17
[9]   Davis BAS et al 2003 *Quat. Sci. Rev.* **22** 1701–1716
[10]   Heikkilä M and Seppä H 2010 *Boreas* **39** 705–19
[11]   Mauri A, Davis BAS, Collins PM and Kaplan JO 2015 *Quat. Sci. Rev.* **112** 109–27
[12]   Willmott CJ and Feddema JJ 1992 *Prof. Geogr.* **44**(1) 84–8
[13]   Novenko EY, Eremeeva AP and Chepurnaya AA 2014 *Veget Hist Archaeobot.* **23** 109–19
[14]   Novenko EYu, Volkova EM, Nosova NB and Zuganova IS 2009 *Quat. Int.* **207** 93–103
[15]   Payne RJ, Malysheva E, Tsyganov A, Pampura T, Novenko E, Volkova E, Babeshko K and Mazei Y 2016 *Holocene* **26** 314-26
[16]   Gregoire LJ, Valdes PJ, Payne AJ and Kahana R 2011 *Clim. Dyn.* **37** 705–19
[17]   Priestley CHB and Taylor RJ 1972 *Monthly Weather Rev.* **100**(2) 81-92
[18]   Tsyganov AN, Babeshko KV, Novenko EY, Malysheva EA, Payne RJ and Mazei YA 2017 *Rus J Ecol.* **48**(2) 191–8
[19]   Charman DJ 2007 Holocene 17 217–27
[20]   Higuera PE, Brubaker LB, Anderson PM, Hu FS and T.A. Brown TA 2009 *Ecol. Monogr.* **79** 201–19
[21]   Krementski KV, Borisova OK and Zelikson EM 2000. Paleontolog. J. 34 (1), 67–74
[22]   Seppä H and Poska A 2004 *Quat. Res.* **61** 22– 31
[23]   Lisitsyna OV, Giesecke T and Hicks S 2011 *Rev. Palaeobot. Palynol.* **166** 311–24
[24]   Schmidt-Vogt H 1977 *Die Fichte – Ein Handbuch in zwei Bänden, Band I Taxonomie, Verbreitung, Morphologie, Ökologie, Waldgesellschaften* (Hamburg: Paul Parey).
[25]   Cienciala E, Lindroth A, Cermak J, Hallgren JE and Kucera J 1994 *J. Hydrol.* **155** 57–71
[26]   Wanner H *et al* 2008 *Quat. Sci. Rev.* **27** 1791–828
[27]   Whitlock C, Higuera PE, McWethy DB and Briles CE 2010 *Open Ecol. J.* **3** 6-23
[28]   Zernitskaya V, Stančikaitė M, Vlasov B, Šeirienė V, Kisielienė D, Gryguc G and Skipitytė R 2015 *Quat. Int.* **386** 70–82